A NOVEL MASS MEASUREMENT TECHNIQUE FOR STORED NUCLEAR MATERIAL

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Abstract

The long-term storage of nuclear material presents unique challenges to instrumentation. The necessity for the equipment to operate reliably for many years in inaccessible locations implies that it will be advantageous to use devices having few parts. This paper will describe a novel device for the measurement of mass (as opposed to weight) suitable for use in modular storage vaults. The device requires that only two electrical parts be buried with the nuclear material (thereby improving reliability) and is easily made nearly independent of operating temperature and humidity without the addition of compensation circuitry.

INTRODUCTION

The weight of an object in storage has been a traditionally acceptable attribute, and there are several commonly used methods for its measurement. These include scales which rely on the extension or compression of springs, and balances which rely on matching the torque produced by standards against that produced by the object whose weight is desired. Common to both kinds of instruments is the ultimate reliance on the force due to gravity that the object under test impresses on the sensitive element(s). Thus, these instruments generate measurements of the product of the local acceleration of gravity and the mass of the object under test.

Versions of these devices with precise electronic readouts are the norm today; however, they are not necessarily the optimal instruments for use in a long-term nuclear material storage facility, which, ideally, has a file-and-forget characteristic. This characteristic is much to be prized because of the minimal costs associated with the maintenance of the storage facility, the static nature of the configuration, and the ease with which items in storage may be monitored. However, because the access to a storage facility will be strictly controlled, and an unscheduled opening can incur a considerable expense, instruments of the utmost reliability are required. Therefore, devices with a minimum of components (electronic and/or mechanical) that need to be placed in the controlled volume containing nuclear material are preferred.

This paper reports on work originally begun to develop a weight sensor that minimized the amount of electronics buried with nuclear material in modular storage vaults (MSVs) at the Oak Ridge Y-12 Plant[1]. Other specifications included insensitivity to temperature and non-condensing humidity, and, of course low unit cost and low to zero maintenance. The device as currently implemented satisfies most of these requirements by implementing a simple system to infer the **mass** of the container from a measurement of the resonant frequency of a mass-spring system.

THEORY

The motion of a mass-spring system is governed by a relatively simple differential equation.

$$m\frac{d^2x}{dt^2}+\alpha\frac{dx}{dt}+kx=F \tag{1}$$

where F is the applied force, m is the mass, x is the displacement from equilibrium, k is the spring constant, and α is a constant describing frictional damping.

Now, consider such a system driven by a linear voice coil. The force is then given by Bli, where B is the constant magnetic induction (provided by a permanent magnet) at the coil, l is the length of wire within the magnetic field, and i is the driving current. In the steady state (at times since the beginning of excitation long compared to $2m/\alpha$, the characteristic decay time of the unforced system) the Laplace transform of equation 1 is

$$m\,s^2X(s)+\alpha sX(s)+kX(s)=BlI(s) \tag{2}$$

Trivial manipulation of equation 2 reveals that X(s) and I(s) are proportional to each other (which must be the case for a linear system). Defining $T_0 = \sqrt{(k/m)}$, and $Q = \sqrt{(mk)}/\alpha$,

$$X(s)=\frac{Bl}{k}\frac{I(s)}{1+\frac{s^2}{\omega_0^2}+\frac{s}{Q\omega_0}} \tag{3}$$

For sinusoidal excitation (s = jT), equation 3 becomes

$$X(j\omega)=\frac{Bl}{k}\frac{I(j\omega)}{1-\frac{\omega^2}{\omega_0^2}+j\frac{\omega}{Q\omega_0}} \tag{4}$$

and it is seen that X(jT) exhibits a resonance. If the motion of the mass-spring system is sensed and the spring constant is known, then the resonant frequency can be inferred from an analysis of the amplitude and phase of the motion. The mass can then be obtained from the definition of T_0. It should be noted that the characteristics of the resonance do not depend on the amplitude of the displacement, the strength of the voice coil's magnet, the physical size of the coil, or the magnetic properties of air or the steel of the assembly. Therefore, the variation (if any) of these parameters with temperature or humidity are of no consequence. In addition, variation of the frictional term (α) affects the Q of the system, but not T_0. It should also be noted that other than establishing the equilibrium compression of the spring, the acceleration of gravity plays no role in this system.

APPARATUS

A voice coil was mounted between two stainless steel plates separated by springs. The magnet assembly was screwed to the movable top plate while the coil was mounted on the fixed bottom plate. This arrangement pre-loaded and seated the springs (the magnet assembly weighed 1862 grams) and, since the coil was on the fixed plate, eliminated the flexion and the possible fatiguing of the coil's connecting cable. The springs were seated on nuts so that the top plate could be leveled.

Two methods of sensing the motion of the top plate were tested. In the first, it was sought to take advantage of the dependence of the inductance of the coil as a function of displacement, and to use a measurement of that inductance as a direct indication of displacement. It was found, however, that the variation of inductance over the range of motion was too small to provide a useful signal.

The second method was to use an inductive pick-up to sense the velocity of the top plate relative to the bottom. A solenoid was mounted on the bottom plate and a permanent magnet fixed to the top plate so that the magnet was driven into the core of the solenoid by motion of the top plate. Because of the use of high-strength Nd-Fe-B magnets, the resulting signal was in between 20 and 100 mV at frequencies between 5 and 50 Hz and peak displacements of about 1 mm. Measurement of the solenoid signal **without** the magnets in place indicated that the voice coil itself did not induce a measurable voltage. The velocity signal was easily converted to a displacement signal by accounting for the factor of T in its amplitude and the relative phase of 90°. The weight pad is shown in Figure 1.

MEASUREMENT AND ANALYSIS

A variable frequency current source was used to generate the excitation, and the signal from the solenoid was used to modify the frequency to drive the system to resonance. Steel weights were weighed, added in steps of approximately 2300 g, and the system was allowed to reach equilibrium after each addition. With the system driven to resonance, the frequency of the current source was averaged over 10 seconds and the average was recorded 10 times. Table 1 shows the mass-frequency data. Note that the sample standard deviation (a measure of the short-term stability of the electronics) is quite small, only about 1 part in 10,000. This implies that the addition or removal of as little as 2 - 4 grams to a 20 kg load is detectable.

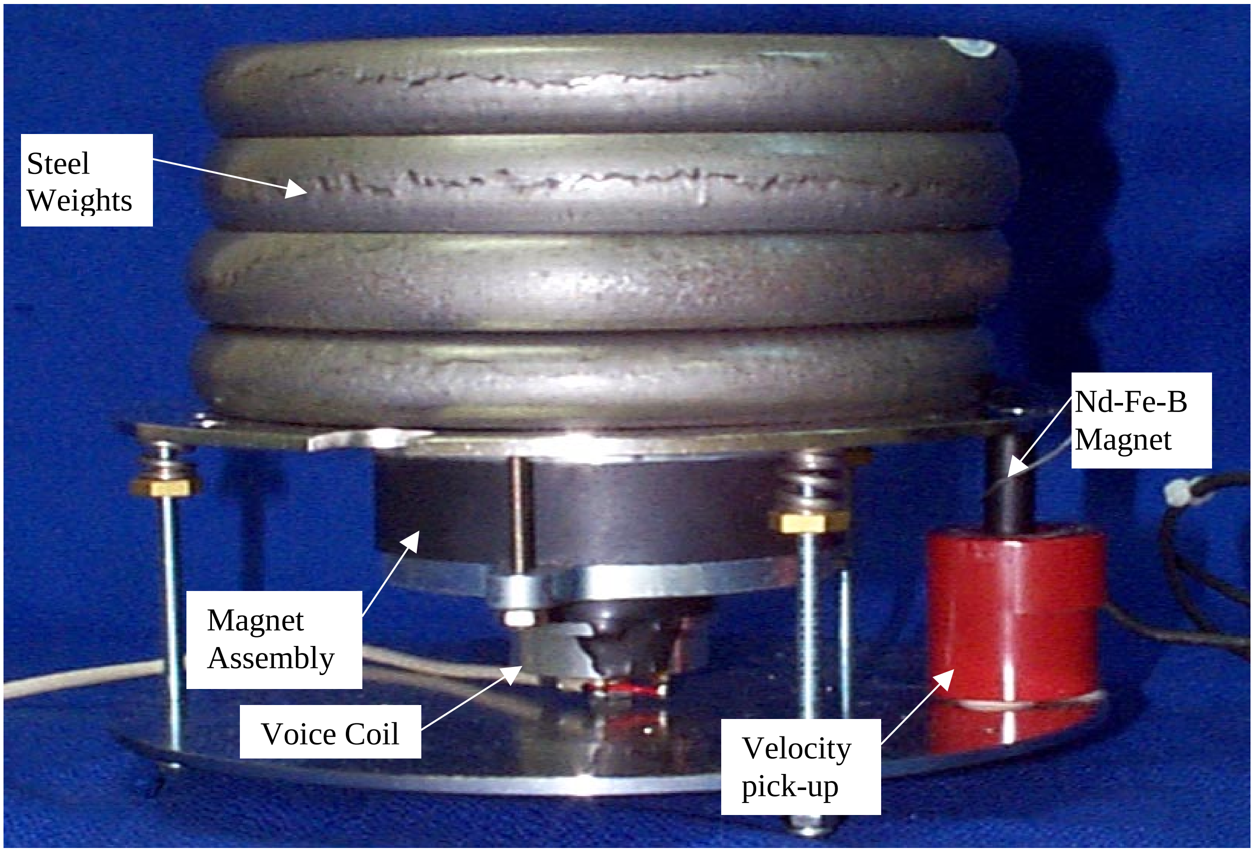

Figure 1. Weight pad showing voice coil and magnetic velocity pick-up.

Table 1. Mass-resonant frequency data

Applied Mass (g)	Measured Resonant Frequency (Hz)	Sample Std. Dev. (Hz)
0	36.6602	0.0117
2305	25.0732	0.0039
4590	20.2578	0.0023
6791	17.5310	0.0005
9017	15.6545	0.0040
11296	14.2327	0.0007
13650	13.0795	0.0011
16051	12.1898	0.0010
18323	11.5019	0.0009
20553	10.9390	0.0007
22879	10.4334	0.0005
25229	9.9783	0.0008

The definition of T_0 implies that mass and $1/f^2$ should be linearly related. A plot of $1/f^2$ from Table 1 versus applied weight (weight added to the top plate) is shown in Figure 2 along with a linear fit to the data. The fit essentially is a measurement of the spring constant and the validity of the model is clearly shown.

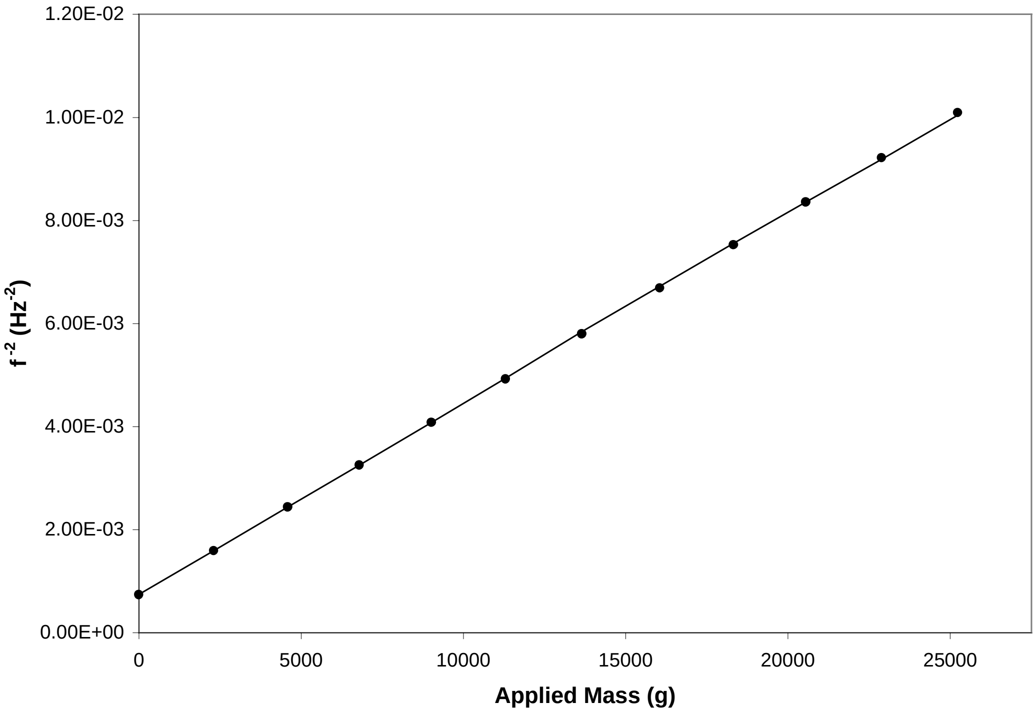

Figure 2. Fit of f^{-2} v. applied mass

The deviation of the inverse model (mass v. $1/f^2$) plotted against true mass is shown in Figure 3 and gives an indication of the overall accuracy of the basic model. From 0 through about 12 kg, the maximum deviation is about 20 g; beyond 12 kg, the deviation is more erratic. However, the worst case is only about 140 g, implying an accuracy of better than 1% over the range 0 - 25 kg.

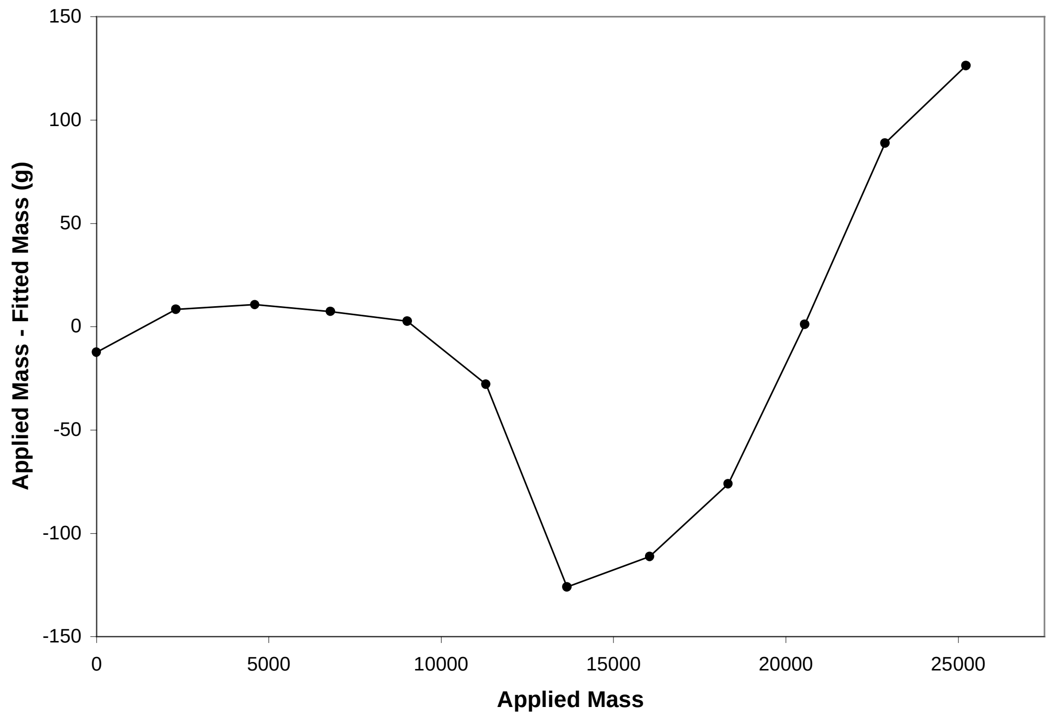

Figure 3. Deviation of fitted mass from true applied mass.

DISCUSSION

The data in the previous section show that the resonant frequency method yields a moderately accurate method to determine the mass of a sample. In addition, the sensitivity is sufficient to detect 100 ppm changes to the sample, which may be more important than absolute accuracy in a storage scenario. The device requires only two coils and two permanent magnets and would not be expected to be particularly susceptible to electromagnetic interference or most external influences. Mechanical shock would manifest itself as an excitation of the natural resonance (to which frequency the external electronics is already locked) and introduce only a phase error relative to the voice coil excitation.

The increase of the absolute error with increasing mass is probably caused by the presence of motions other than motion parallel to the axis of the voice coil. The mass spring system has, in addition to that motion, degrees of freedom parallel to the surface of the plate and twisting degrees of freedom. As the mass on the top plate increases, the Qs of motions perpendicular to the axis of the voice coil also increase, making them more prominent and excitable by small misalignment of the voice coil and its magnet and/or the asymmetric placement of mass on the top plate. If these other modes of oscillation have natural frequencies near that of the axial motion, then the model implied by equation 3 and the subsequent discussion does not apply and the analysis based on a single natural frequency is incorrect. Nevertheless, the data in Figure 3 show that the simple physical model of the mass-spring system is very nearly correct over a large mass range.

The design presented in this paper lends itself to using a single adjustable current source multiplexed to a large number of weight pads. Analog switches or solid state relays are readily available to route the excitation and sensing signals. The resulting implementation requires a minimum of electronics outside a storage array and no components subject to a significant probability of failure. The main modes of failure of the weight pad are expected to be changes of spring constant brought on by fatigue of the springs or changes in ambient temperature, an increase of internal friction (and concomitant decrease of Q) leading to a decrease of the amplitude of the sensing signal, decrease of the strength of the voice coil magnet, and deterioration of the voice and/or pick-up coils. Of these, the most serious are the changes of spring constant and the deterioration of the coils. The others can be reduced or eliminated by proper selection of spring and magnet material, by minimization of contacting surfaces, and incorporation of an automatic gain control in the sensing/driving electronics.

Changes of spring constant because of either fatigue or work-hardening of the spring, or change in ambient temperature leads to a change in the resonant frequency of the system. This, in turn, leads to a variation of the measured mass of the sample. However, such changes will probably manifest themselves as a long-term drift possibly combined with a cyclic variation with 24 hour period. Selection of spring materials with small coefficients of thermal expansion, and maintaining small peak-to-peak amplitude of motion will tend to minimize these effects. In addition, in the absence of tampering, a computer-controlled system can always recalibrate itself if the measured mass drifts outside of pre-defined limits.

Deterioration of the voice coil, either by loss of insulation between turns or by arcing between them can render the system inoperable. Arcing is not likely to be a problem since proper selection of coil parameters and magnet assembly will lead to low driving voltages. The key to voice coil design may well be the selection of waterproof, oxidation resistant lacquers with which to coat the coil wire. The authors' experience with loudspeakers (which, of course, contain a voice coil and magnet), however, indicate that except for high voltage or current spikes caused by lightning or malfunction of the driving electronics, voice coils are essentially indestructible.

In summary, measurements of the characteristics of an electromagnetic system to infer the mass in a mass-spring system indicate that this design is sufficiently accurate for monitoring activities in a long-term storage facility. The system is expected to be sufficiently robust that the lifetime of the equipment buried with the nuclear material should be measured in decades.

Reference

1. Managed by Lockheed Martin Energy Systems, Inc., for the U.S. Department of Energy under contract DE-AC05-84OR21400.